AN EVALUATION OF AN EXPERIMENTAL METHOD FOR STUDYING SQUEEZE FILMS

Corwin Anson Olds

AN EVALUATION OF AN EXPERIMENTAL METHOD
FOR
STUDYING SQUEEZE FILMS

* * * * * *

Corwin Anson Olds

AN EVALUATION OF AN EXPERIMENTAL METHOD FOR STUDYING SQUEEZE FILMS

by

Corwin Anson Olds

Lieutenant, United States Navy

Submitted in partial fulfillment
of the requirements
for the degree of
MASTER OF SCIENCE
IN
MECHANICAL ENGINEERING

United States Naval Postgraduate School
Monterey, California

1 9 5 6

This work is accepted as fulfilling
the thesis requirements for the degree of

MASTER OF SCIENCE

IN

MECHANICAL ENGINEERING

from the

United States Naval Postgraduate School

PREFACE

Wherever motion is constrained by a bearing, there will exist a "squeeze film" between two surfaces of the bearing having a normal relative velocity.

The load carrying capacity of such films has been of theoretical interest since 1874 when Josef Stefan solved the problem for flat circular plates. Nevertheless, there has been a lack of experimental data on the subject. It is the purpose of this paper to describe and evaluate one method by which such data might be experimentally obtained.

The writer wishes to thank Professors E. K. Gatcombe and S. H. Kalmbach for their generous encouragement and assistance.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

TABLE OF SYMBOLS AND ABBREVIATIONS

C.R.O.	- Cathode ray oscilloscope
L	- Light source
O.F.	- Optical flat
B.T.	- Barium titanate
F	- Force
cm	- Centimeter
m	- Mass
r	- Radius of circle, half amplitude of vibration
w	- Circular frequency of oscillation ($= 2\pi f$)
WT	- Weight (lbs.)
Δh	- Peak to peak distance of pressure trace on oscilloscope
Δe	- Peak to peak calibrated strain (microinches/in)
f	- Frequency of oscillation (cycles per second)
u	- Index of refraction
λ	- Wave length
t	- Film thickness
n	- Any integer
S	- Resolving distance of a lens
i	- One-half the angle subtended by a lens
Δs	- Peak to peak distance of strain gauge trace on oscilloscope
Δss	- Mean distance between strain gauge calibrating lines on oscilloscope
M	- Bridge balancing resistor (megohms) on the BA-1 strain gauge indicator

CHAPTER I

SUMMARY

1. Introduction.

A survey of experimental methods for measuring the minimum oil thickness in journal bearings by Brotherton in 1952 indicates that

a. Direct determination of minimum oil film thickness is very difficult, and

b. An optical interferometer type of measurement would probably be practical.

The problem of measuring the thickness of a squeeze film between two circular flats having only normal relative motion is a simplified version of the same problem. Preliminary work on the adaptation of optical interferometer methods to squeeze films was done by Appert in 1953 and by Bridwell in 1954 utilizing equipment designed by Professor E. K. Gatcombe in 1952. The results of this work indicated that the measurement of thin squeeze films of air between two optical flats by interferometer methods was feasible. No attempt was made to measure the load carrying capacity of the film.

The interferometer method results in an incremental measurement of thickness as opposed to a continuous measurement. Furthermore, the interferometer system as used by Appert and Bridwell measures only a change in thickness as opposed to measuring the absolute thickness of the film. Improving upon

these deficiencies, plus the simultaneous measurement of load carrying capacity of the film became the objective of this thesis.

2. General Methods Employed.

a. Load carrying capacity. The squeeze film was formed between two optical flats one inch in diameter. The upper flat was held in position while the lower flat was forced against it by means of hydraulic pressure acting on a thin rubber membrane. A barium titanate pressure pickup was inserted between the flat and the membrane, and the output fed directly to a double trace cathode ray oscilloscope.

b. Film thickness. It was planned to measure film thickness by projecting the image of a mark inscribed on the moving flat through a slit and thence upon a photomultiplier tube. The output of this tube was to have been displayed on the other trace of the cathode ray oscilloscope. The C.R.O. would have simultaneously displayed a continuous indication of both load carrying capacity and film thickness as a function of time. It was planned that the photomultiplier system would be calibrated by using a channel spectrum interferometer system.

3. Findings.

The barium titanate pressure pickup furnishes an excellent method of detecting transient pressure waves, if properly calibrated. The calibration, however, is difficult. The channel spectrum system was completed and tested with encouraging results. The photomultiplier system was not completed.

CHAPTER II

DESIGN

1. The overall system:

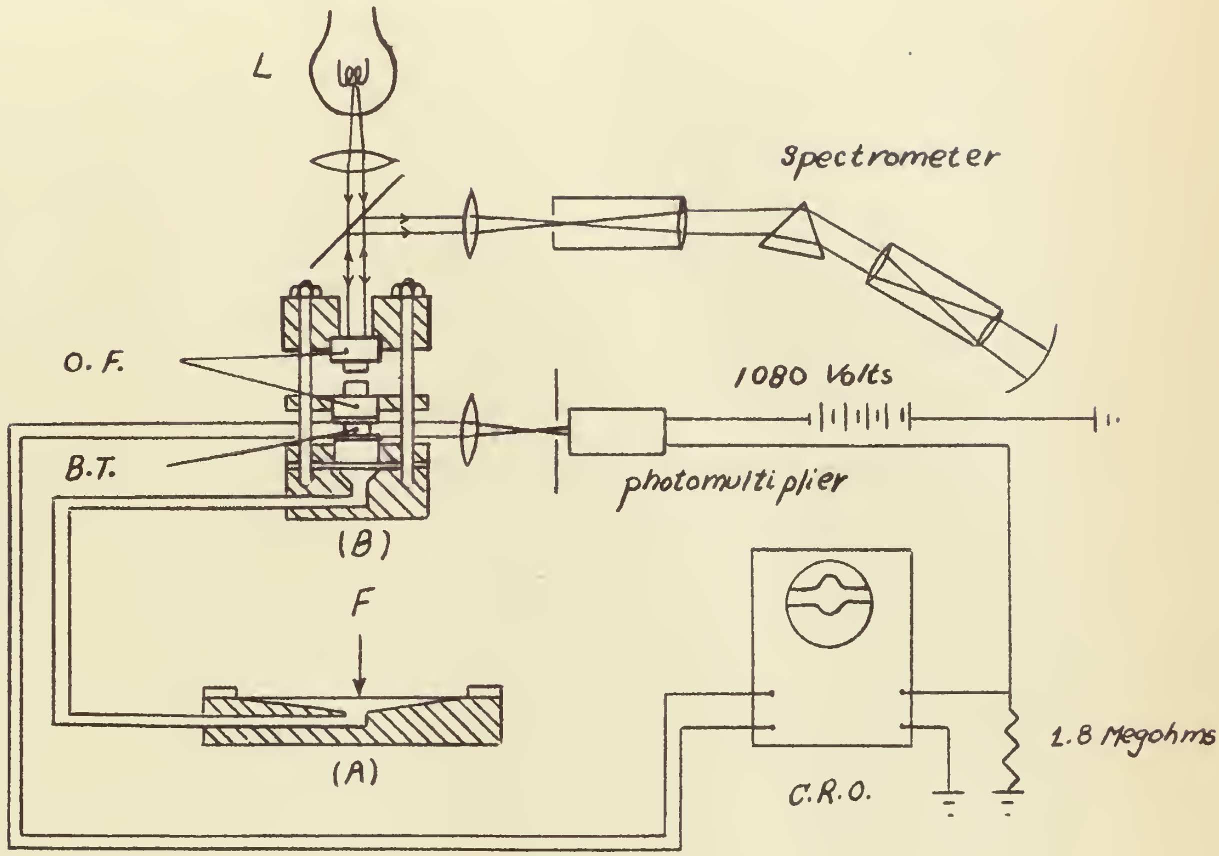


Fig. 1. The overall system

The pump end of the system (A) consisted of an aluminum cup covered with a steel diaphragm made from 0.005" shim stock. A force on this diaphragm was transmitted through the liquid to the (B) end which consisted of a similar aluminum cup covered by a thin rubber diaphragm (a dental dam). Flexure of the rubber diaphragm forced upward an aluminum piston supporting the B.T.

pickup and the lower optical flat. This exerted a force on the squeeze film separating the two flats, the upper one of which was held firmly to the base (B) by four 0.25" brass bolts. Motion of the lower flat was detected by interference of the light from L as viewed by the spectrometer and was planned to be detected by the photomultiplier tube. The C.R.O. was to have displayed the simultaneous output from the B.T. and photomultiplier tube.

The pump end (A) was made several times larger in diameter than the (B) end in order to insure a sufficient displacement of the fluid to overcome any expansion of the tubing connecting the two ends as well as to allow for any compressibility of the fluid itself. The fact that a greater force would be required at (A) for a given force at (B) was accepted inasmuch as the forces on the flats were to be kept low, both to prevent damage to the flats and to minimize the effects of the elongation that might be expected in the retaining bolts. The steel diaphragm provided adequate strength for this greater force.

The use of a natural rubber diaphragm at the (B) end dictated the use of water as the hydraulic fluid. The distance between the (A) and (B) ends was four feet. This comparatively long length of tubing was used to provide a measure of vibration isolation for the (B) end. However, it also resulted in a throttling effect which severely limited the rate of loading of the squeeze film.

Every effort was made to locate the B.T. pickup as close

to the oil film as possible. With the equipment available it was decided most feasible to locate it immediately below the lower optical flat. It was recognized that the force measured was not the actual force in the squeeze film, being less by the amount contributed by the inertia of the flat itself, and also containing an error due to the finite time required for the pressure wave to transit the flat. The latter error was considered to be negligible for frequencies under one kilocycle which was the planned experimental range.

Some effort was made to make the lower optical flat the B.T. itself. Efforts were made to polish the B.T. and vacuum deposit an aluminum layer on it. The B.T. available was too porous to make vacuum plating satisfactory. There were indications that a chemical process would deposit enough material to allow for optical polishing. This being a lengthy project in itself, the idea was not pursued any further. Nevertheless, for accurate measurement in the film itself, making the B.T. one of the containing flats is imperative.

2. The pressure pickup system. (Calibration of B.T.)

Barium titanate as a transient pressure sensing device is accurate, quick to respond, and delivers a signal of sufficient strength to be displayed directly on a C.R.O. without additional amplification. Commercial pressure pickups are available for as low as $225.00[1] which have an output of 40 millivolts per psi and cover a substantial pressure range with a flat frequency response from two cycles per second to nine kilocycles. Barium

[1] Endevco Corp. Pasadena, California.

titanate responds only to transient signals, making calibration a difficult procedure.

In addition to the effects of pressure, the signal output is proportional to the amount of B.T. used. Ordinary phonograph pickups use only a very small amount of B.T. The commercial pressure pickups use plugs on the order of 0.25 inches in diameter. Lacking facilities for impressing the very high polarizing potentials required for optimum sensitivity (about 40,000 volts/cm), sufficient sensitivity was obtained by using a plug approximately one inch in diameter and one-eighth of an inch thick.

Three such plugs were carefully cut from a piece of scrap through the courtesy of the Dental Department of the U. S. Naval Postgraduate School. The rough plugs were then placed between two wooden plugs on a lathe and the edges sanded smooth. One plug was selected for experimenting with further fabricating methods and was eventually destroyed. The other two plugs were successfully polarized, as follows:

Polarizing electrodes were cut from 0.003" thick copper shim stock and cemented to the B.T. with copper dental cement. The unit was then inserted in an insulating clamp and immersed in a beaker filled with ordinary lubricating oil. The oil was subsequently heated to 260° F. and a potential of 2160 volts d.c. applied across the electrodes. The high temperature was maintained for five minutes in order to insure uniform heating throughout. The heat was then removed and the B.T. allowed to

cool in the oil to room temperature. The voltage was maintained until room temperature was reached. The 1.5 Megohm current limiting resistor was placed in series with the battery for safety.

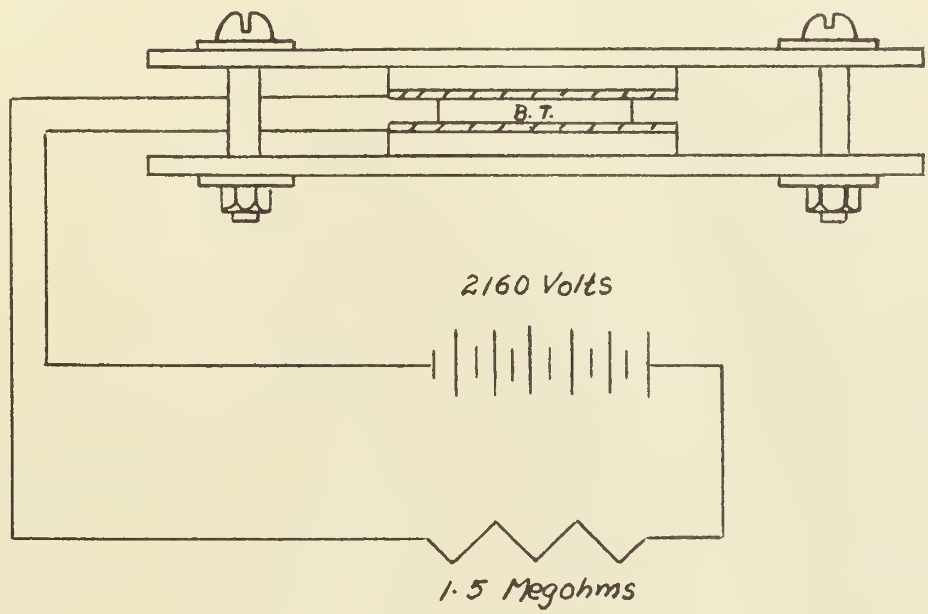


Fig. 2. Clamp for polarizing barium titanate

Both barium titanate plugs were successfully polarized with a minimum of trouble. Sensitivity obtained was such that they gave good response to a loud shout from a distance of a few inches.

The calibration of the B.T. proved to be much more difficult than the polarizing and far less successful. Several methods of calibration were attempted.

The basis of calibration for all the methods attempted was to vibrate the pressure pickup on a Westinghouse Fatigue Motor

(Type GS) at a known frequency and displacement with and without a calibrating weight resting on top. When the pressure pickup was vibrated without a weight on top of it, the signal output would be an indication of acceleration forces acting within the B.T. itself. When the weight was added, the increased output signal would be an indication of the pressure on the B.T. resulting from the inertia of the weight and would be easily computable from the expression:

$$\Delta F = \Delta m r w^2$$

where Δm = mass of the calibrating weight

$2r$ = displacement through which the weight oscillated

w = circular frequency of the motion in radians/sec.

a. Non-preloaded. The general shape of the response versus pressure curve for B.T. is shown below:

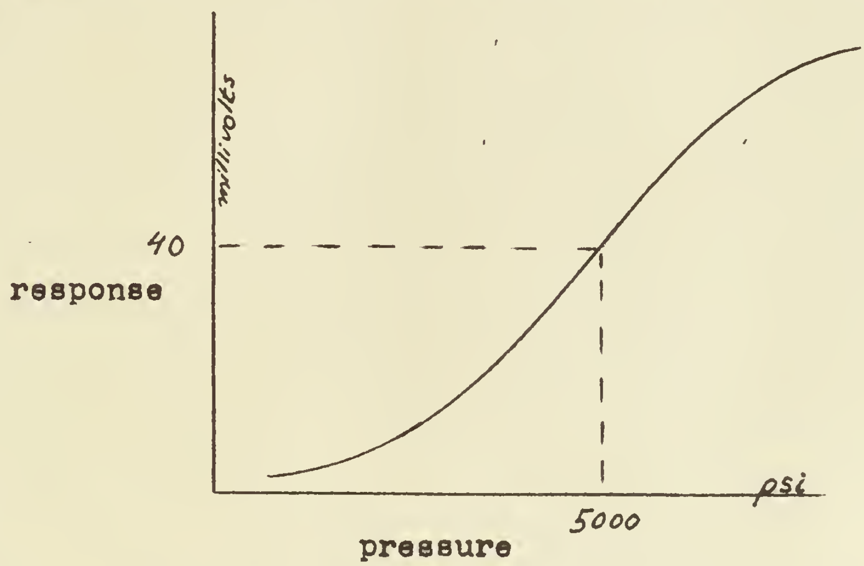


Fig. 3. Response vs. pressure of barium titanate

The central linear portion of the curve occurs at pressures on the order of thousands of pounds per square inch. Since the

plug used in this case was one inch in diameter (area = 0.785 in^2), it was not considered feasible to attempt to preload sufficiently to reach the linear portion of the curve. On the other hand, an examination of the lower portion of the curve shows an area of near linearity, although with low response, at low pressures. Since the size of the plug was large enough to give adequate signal at low pressure (as demonstrated by shouting at it) and since it was planned to use it as a pressure pickup only at low pressures, it was decided that the most feasible plan of approach would be to encase the B.T. in a holder which would prevent any preloading, place a weight on top of this unit and vibrate the entire system at a known frequency with a known displacement. This was done with unsatisfactory results.

One of the major difficulties with the non-preloaded system was the method of attaching the electrodes to the B.T. When vibrating at frequencies producing accelerations of more than one "g", the calibrating weight exerted a tensile force on the electrodes. While it was easy enough to glue weights to the electrodes with ordinary household cement, no satisfactory method was discovered of getting a strong, non-preloading, electrically conducting bond between the B.T. and the electrodes. Aluminum cement, copper dental cement, zinc dental cement, and bismuth solder were tried without success. The use of ordinary solder was prohibited because of temperature considerations. The final solution was to manufacture a plastic ring container

0.002" thicker than the B.T. Brass plate electrodes were then fastened to the ring with screws, the space between the electrodes and the B.T. having been filled with sufficient silver paste to make electrical contact and transmit pressure from the electrodes without preloading. This system met with fair success.

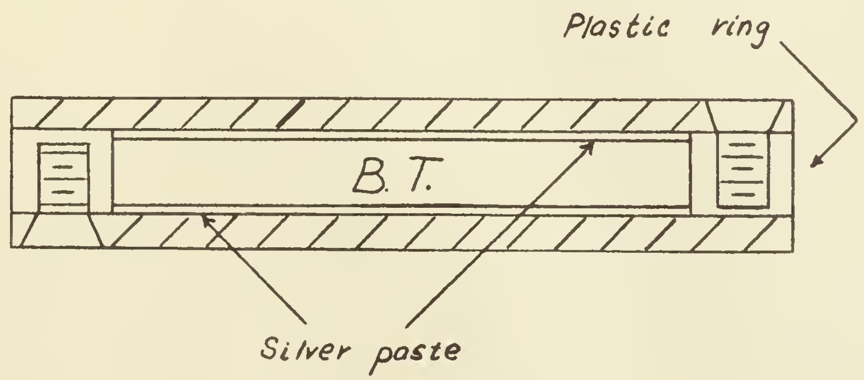


Fig. 4. Non-preloaded, plastic ring unit.

b. Preloaded. In view of the troubles experienced with a non-preloaded pressure pickup, it was determined that a certain amount of preloading would be required. The feasibility of applying sufficient preloading to reach the linear portion of the curve was considered but abandoned because of its incompatibility with elements previously designed and built. Accordingly, it was decided to keep the preloading small in order to stay as close to the low pressure near-linear region as possible, preloading only a sufficient amount to accomplish structural strength. The unit sketched in Figure 5 was the result.

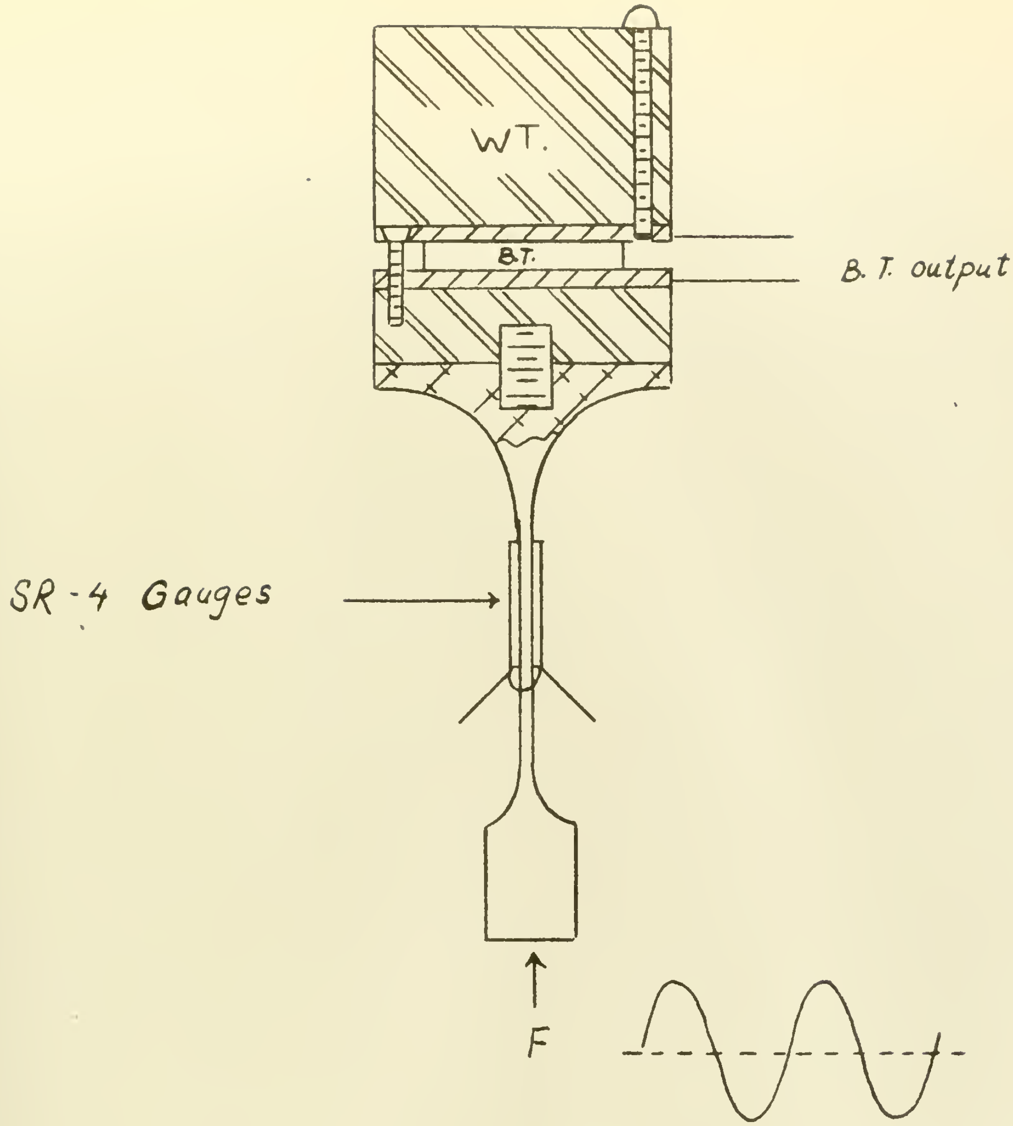


Fig. 5. Preloaded Unit

Attempts to calibrate the non-preloaded unit indicated that insufficient displacement (r) to measure optically could be obtained at high frequencies. It was then decided to utilize a holder as in the sketch above which would be essentially a column in alternate compression and tension. The holder was constructed of aluminum with a gauge cross section of 0.050 x 0.400 inches. Two SR-4 strain gauges type A-7 were placed one

on each side of the column. An Ellis BA-1 strain gauge indicator coupled to a C.R.O. via a Hewlett-Packard 40 db amplifier was used to display the unit strain existing in the column section of the holder. This strain was taken to be proportional to the pressure existing on the B.T.

The results of this system, though better than the previous system, were still far from gratifying. Both the BA-1 indicator and the Hewlett-Packard amplifier were so microphonic as to render the output signal completely obscured by noise at the higher frequencies. At the lower frequencies large displacements were necessary in order to obtain sufficient signal, but this resulted in a distorted wave form. Efforts to improve the ratio of signal to noise and to minimize distortion consisted of increasing the mass of the calibrating weight from 0.506 lbs. to 2.71 lbs., and of using long shielded leads to permit placing of the indicator and amplifier in a different room from the vibration motor. Both of these efforts resulted in some improvement but still left much to be desired. The B.T., requiring no amplification other than the C.R.O. itself, produced a strong clear signal at all times.

Although the signal from the SR-4 strain gauge left much to be desired, a calibration was attempted in three different ways.

1. With a constant power output from the oscillator controlling the vibration motor, readings were taken over a spectrum of frequencies; first, with the 0.506 calibrating

weight in place and secondly, without the weight. The results were inconclusive.

2. Since the amplitude of the vibration was different with or without the calibrating weight at a given oscillator power output, another set of readings were taken at two low frequencies in the range where optical measurement of the displacement was feasible. At each frequency, runs were made with and without the 0.506 lb. calibrating weight in place. Great care was taken to obtain the same amplitude of vibration for each pair of points. The results of these runs are shown in Fig. 6. The fact that the signal output is not linear with pressure is quite evident. If the B.T. were to be used at a known fixed frequency in the range where optical calibration was feasible, this method of calibration would have been sufficient. However, the difference in signal output between these two runs is not proportional to w^2 as expected. It is evident that there is a frequency dependent variation which had not been determined.

3. With the above in mind, a third calibration was attempted by using the SR-4 strain gauge over a spectrum of frequencies with a larger (2.71 lbs.) calibrating weight on the B.T. The results of these runs are shown on Fig. 7.

Note that both curves exhibit a maximum at low frequencies. There are two possible explanations for this:

a. The vibration motor with the experimental equipment in place exhibited mechanical resonance at several frequencies.

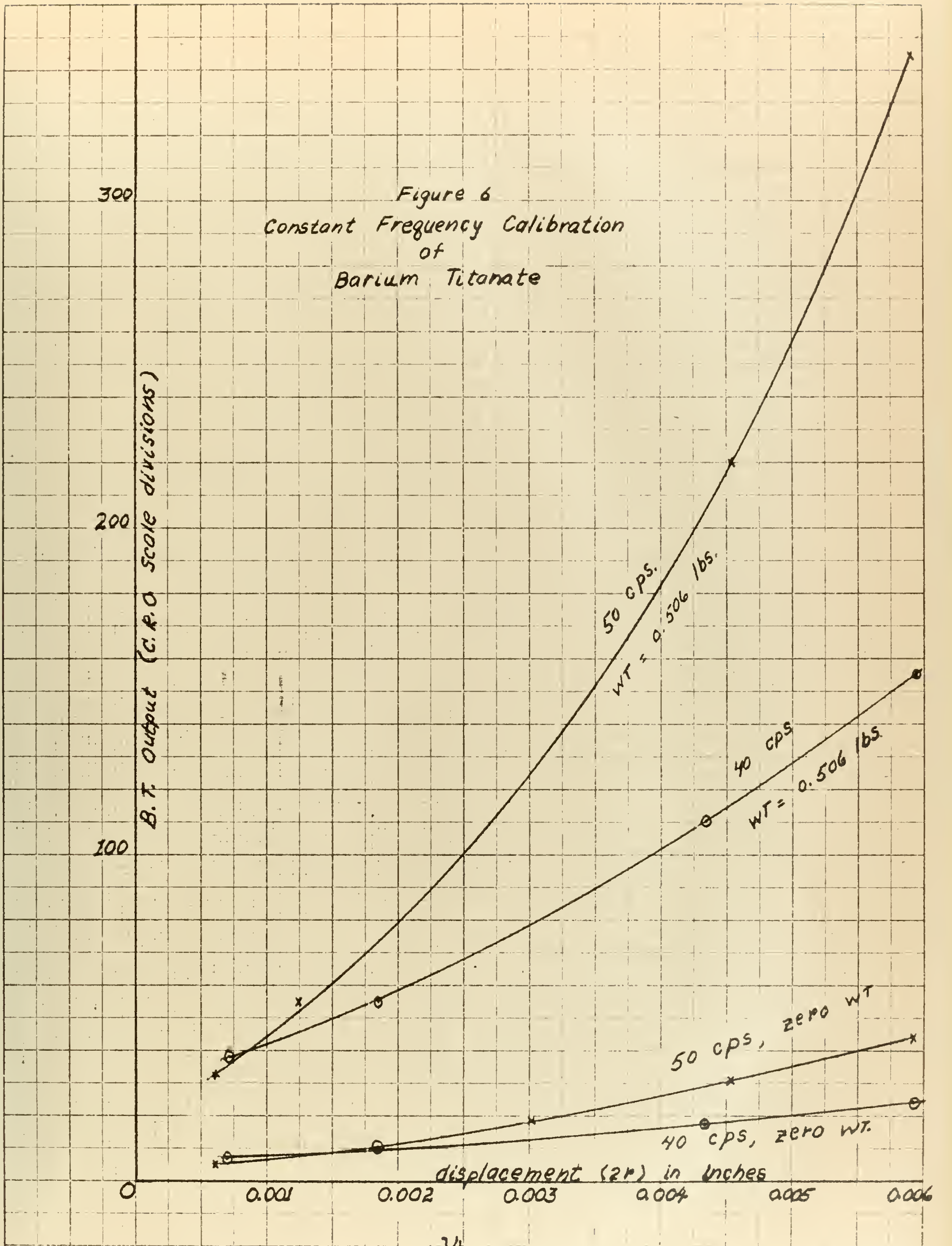


Figure 6
Constant Frequency Calibration
of
Barium Titanate
B.T. Output (C.R.O. Scale divisions)
displacement (2r) in inches
300
200
100
0
0.001
0.002
0.003
0.004
0.005
0.006
50 cps.
WT = 0.506 lbs.
40 cps
WT = 0.506 lbs.
50 cps, zero WT
40 cps, zero WT.

15

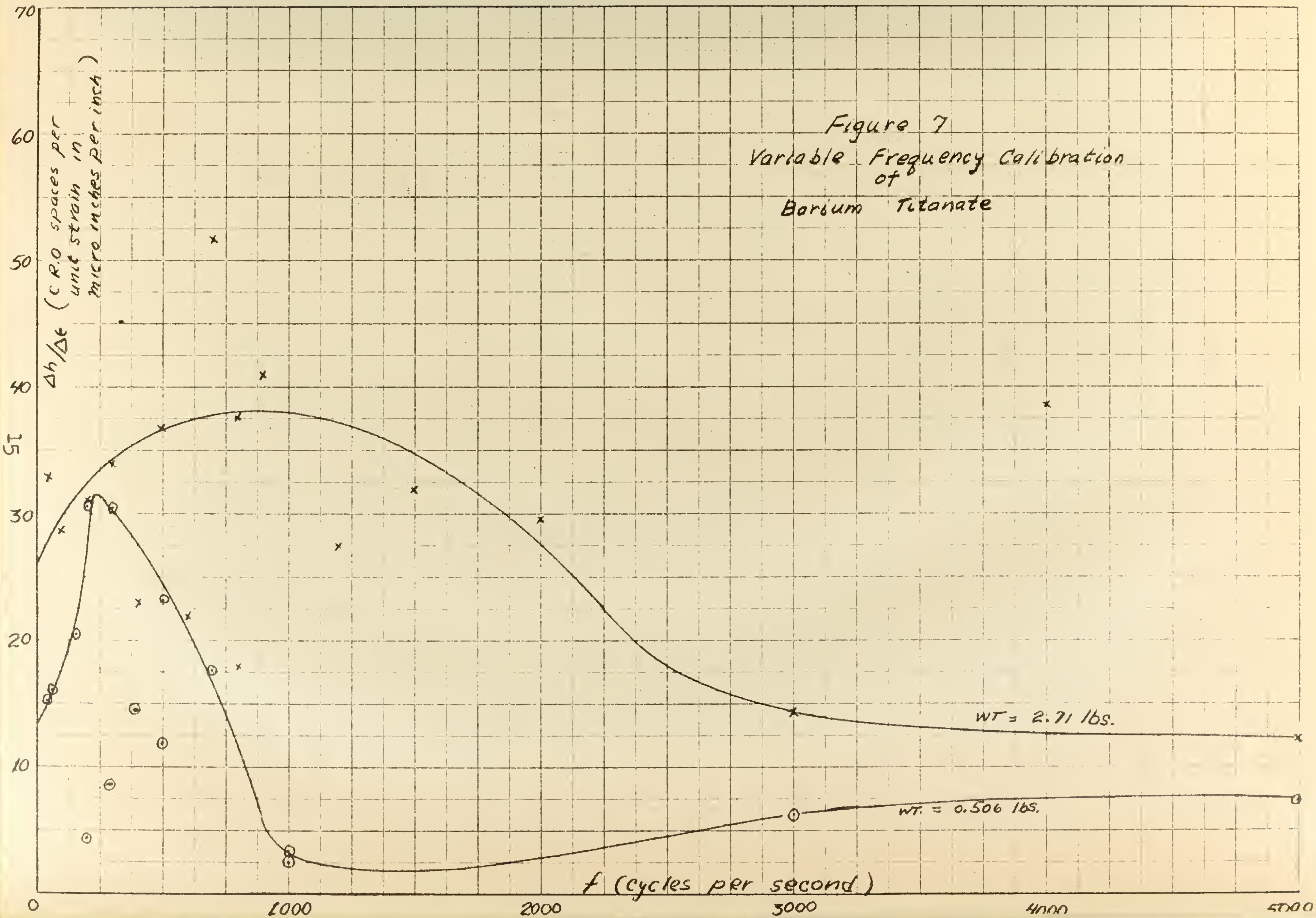


Figure 7
Variable Frequency Calibration of Barium Titanate
Δh/Δe (C.R.O. spaces per unit strain in micro inches per inch)
f (Cycles per second)
WT = 2.71 lbs.
WT. = 0.506 lbs.
0
10
20
30
40
50
60
70
1000
2000
3000
4000
5000

In the lower resonant frequencies a considerable increase in the amplitude of oscillation was experienced. This resulted in vibrating the electrical leads several hundredths of an inch in the stray magnetic field about the motor, inducing an electric potential in the leads. Efforts were made to eliminate this effect by using shielded leads as far removed from the center of the motor as possible and by bringing the leads in as parallel to the magnetic field as possible. Apparently this was not sufficient.

b. Mechanical vibration waves within the calibrating column at certain frequencies produced a node or near-node in the region of the strain gauge. This resulted in an abnormally small signal from the strain gauge for a given pressure on the barium titanate. In order to minimize this effect, it would be necessary to locate the strain gauge as close as possible to the barium titanate.

At the higher frequencies both curves approach a limiting value of $\Delta h/\Delta e$ equal to 9.5 cathode ray oscilloscope spaces per unit strain (microinches per inch). In this region actual motion of the unit was negligible, eliminating the induced electrical error.

Time did not permit further investigation into the calibration problem.

3. The optical interferometer (channel spectrum) system.

The channel spectrum system is a convenient method for measuring the actual thickness of thin films under static conditions. White light passes through a collimating lens and is focused on the film between the two flats. Multiple reflections from both faces of the film results in destructive interference at several wave lengths. The spectrum of the reflected light will show dark bands (channels) resulting from this interference.

Numbering the dark bands with arbitrary integers from one end of the spectrum to the other, we can say

(1) $$n \lambda_1 = 2\,u\,t$$

where λ_1 = wave length at which dark band number n occurs

u = index of refraction of the film fluid

t = thickness of the film

Some other dark band occurs at wave length λ_2. Thus

(2) $$(n + \Delta n)\lambda_2 = 2\,u\,t$$

Equating (1) and (2) $\quad n\lambda_1 = n\lambda_2 + \Delta n \lambda_2$

(3) $$n = \frac{\Delta n \lambda_2}{\lambda_1 - \lambda_2}$$

Substituting (3) in (1)

(4) $$t = \frac{\Delta n \lambda_1 \lambda_2}{2u(\lambda_1 - \lambda_2)}$$

The film thickness is then easily calculated from the number of dark bands occurring between any two wave lengths

of the spectrum.

The wave length at which any dark band occurs is obtained by first calibrating the spectrometer against the known lines of a mercury spectrum. A graph is made of wave length versus the viewing angle of the spectrometer. The wave length of any dark band is then obtained by entering the graph with the angle at which it is viewed. The calibration chart used in these tests is included in the appendix as Fig. 12. The index of refraction for the oil was determined to be 1.485 by means of an Abbe refractometer.

The useful spectrum of wave lengths without resorting to photographic techniques is from 4000 to 6000 angstroms. Assuming that $\Delta n = 1$, we can see that the minimum film thickness measurable by this means is 1.59×10^{-5} inches. In actual practice the minimum film thickness will be somewhat greater because the dark bands tend to spread out and lose their clarity as Δn decreases.

Use of channel spectrum method for measuring thickness is restricted to static conditions. Movement of the dark bands during loading was observable, and it was noted that ten to twenty seconds were required before equilibrium was attained. This demonstrated the time dependence of the load carrying capacity of squeeze films.

The film thickness under static conditions was measured. The results are shown in Fig. 8. The loading in this case resulted from placing several known weights on the diaphragm

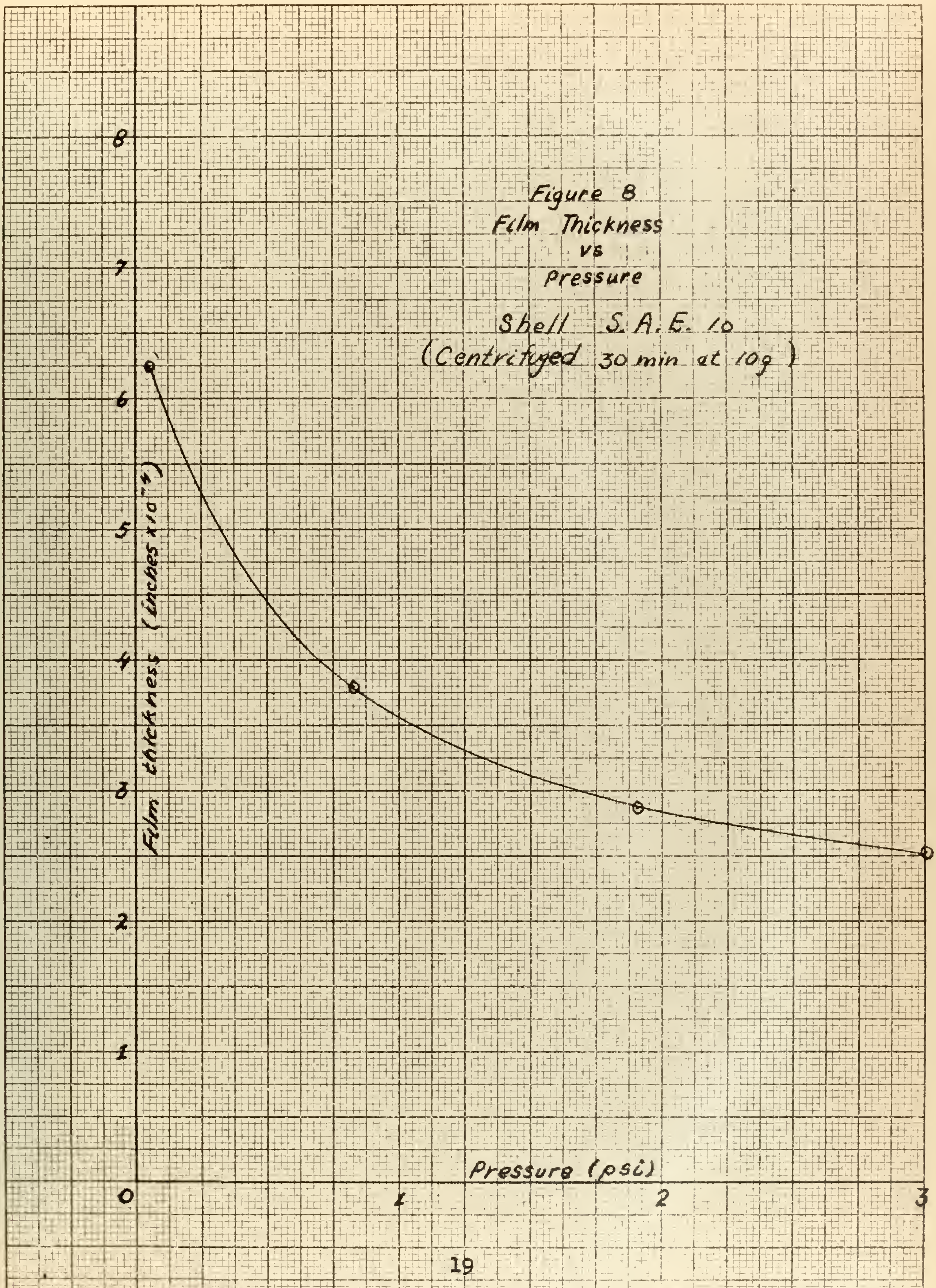


Figure 8
Film Thickness
vs
Pressure
Shell S.A.E. 10
(Centrifuged 30 min at 10g)
Film thickness (inches x 10⁻⁴)
Pressure (psi)
0
1
2
3
4
5
6
7
8

of the (A) end. The pressures represented in Figure 8 were then computed from the relative areas of the diaphragms. The weight of the composite piston in the (B) end, including the optical flats and the B.T., was taken into account. The effects of friction and restraining force of the diaphragms were neglected, there being no motion of the piston or the diaphragms from the neutral position.

4. The photomultiplier tube system.

The sub assemblies for this system were manufactured and were awaiting installation. The photomultiplier tube was tested for response with promising results.

The major problem in this system was the locating of a lens having sufficient resolution to detect the very small (1×10^{-5} inch) changes in film thickness expected.

The theoretical equation for determining the resolving power of a lens is

$$s = \frac{1.22\lambda}{2 \sin i}$$

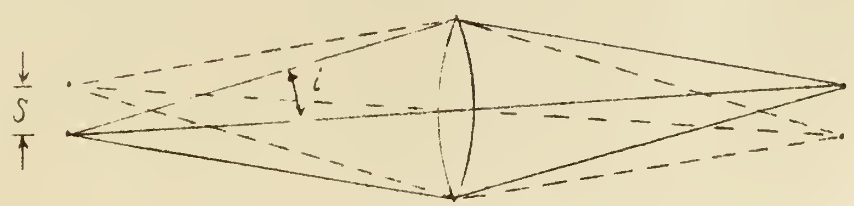


Fig. 9 Resolving power of a lens

s = distance between the points to be resolved

i = One-half the angle subtended by a lens as shown

λ = The effective wave length (5600 Angstroms for white light)

Abbe has investigated in detail the problem of the resolving power of a lens and has concluded that the factor 1.22 may be eliminated in practice. Furthermore, he has determined that $s = 0.71 \times 10^{-5}$ inches is the minimum practical separation that can be resolved. To do so requires a lens of 1.6 numerical aperture.

A lens having a numerical aperture of 1.6 and a focal length of two to three inches was considered to be optimum for resolving the movement of the optical flats. These dimensions correspond to a high quality lens for a small camera. Neither such a lens nor money to purchase one being available, an extensive search for a suitable substitute was undertaken. An f/1.6 lens for a 16 mm. projector was tested and rejected. The lens from a 16 mm. Navy aircraft gun camera was also tested and rejected. The final choice was an objective from a pair of 7 x 50 binoculars loaned from a nearby naval air station. The focal length of that lens was approximately eight inches, but the resolution was far better than any other lens tested.

CHAPTER III

CONCLUSIONS

The barium titanate pressure pickup is an excellent means of determining transient pressures provided it can be properly calibrated.

The absolute thickness of the oil film was successfully measured under static conditions by means of the channel spectrum system. This method of measurement is straightforward and simple in operation. It should serve as an excellent method for calibrating a system such as the photomultiplier system for measuring dynamic film thicknesses.

It is felt that the experimental determination of the load carrying capacity of squeeze films under dynamic, and particularly impact, loads is worthy of further investigation. It is also considered that the basic methods attempted by this author are sound and worthy of more complete development. If such investigation is to be conducted at the U. S. Naval Postgraduate School, it is recommended that the project be subdivided into at least the five steps listed below.

a. A complete redesign of the equipment used by this author. No more should be attempted in one year than the detailed plans, list of material, price list, and probable source of supply for each item.

b. All special units such as lenses, B.T., etc. should be ordered prior to the time assigned for thesis work. This

much could be done by the supervising department.

c. Assembly, fitting and adjustment of the entire unit.

d. Manufacture and calibration of the pressure pickup and the displacement systems.

e. Operation to obtain data.

It is noted that the above divisions correspond roughly to those of the previous work done in this field. Any redesign of the basic equipment used in these tests should consider:

a. The necessity of fixing all optical parts to the same base to insure rigidity. However, provisions must be incorporated for the final alignment and focusing of each part while in the fully assembled condition.

b. A stiff spring should be provided to insure separation of the optical flats when the pressure is released.

c. The optical flats should be immersed in an oil reservoir to a depth that will insure the interfaces being covered with oil at all times.

d. If hydraulic loading is to be utilized, a small hand pump and bourdon pressure gauge should be included. The distance between the (A) and (B) end should be minimized.

e. Inasmuch as barium titanate pressure pickups having a flat frequency response from two cycles per second to nine kilocycles or more are commercially available, it is strongly recommended that such a pickup be obtained either for direct use, or for a standard to which a locally manufactured pickup could be calibrated. In the event that it is impossible to

obtain such a pickup, then it is recommended that calibration of the locally made pickup be calibrated by squeezing against a "rigid" beam instead of by freely vibrating it. (See Figure 10.)

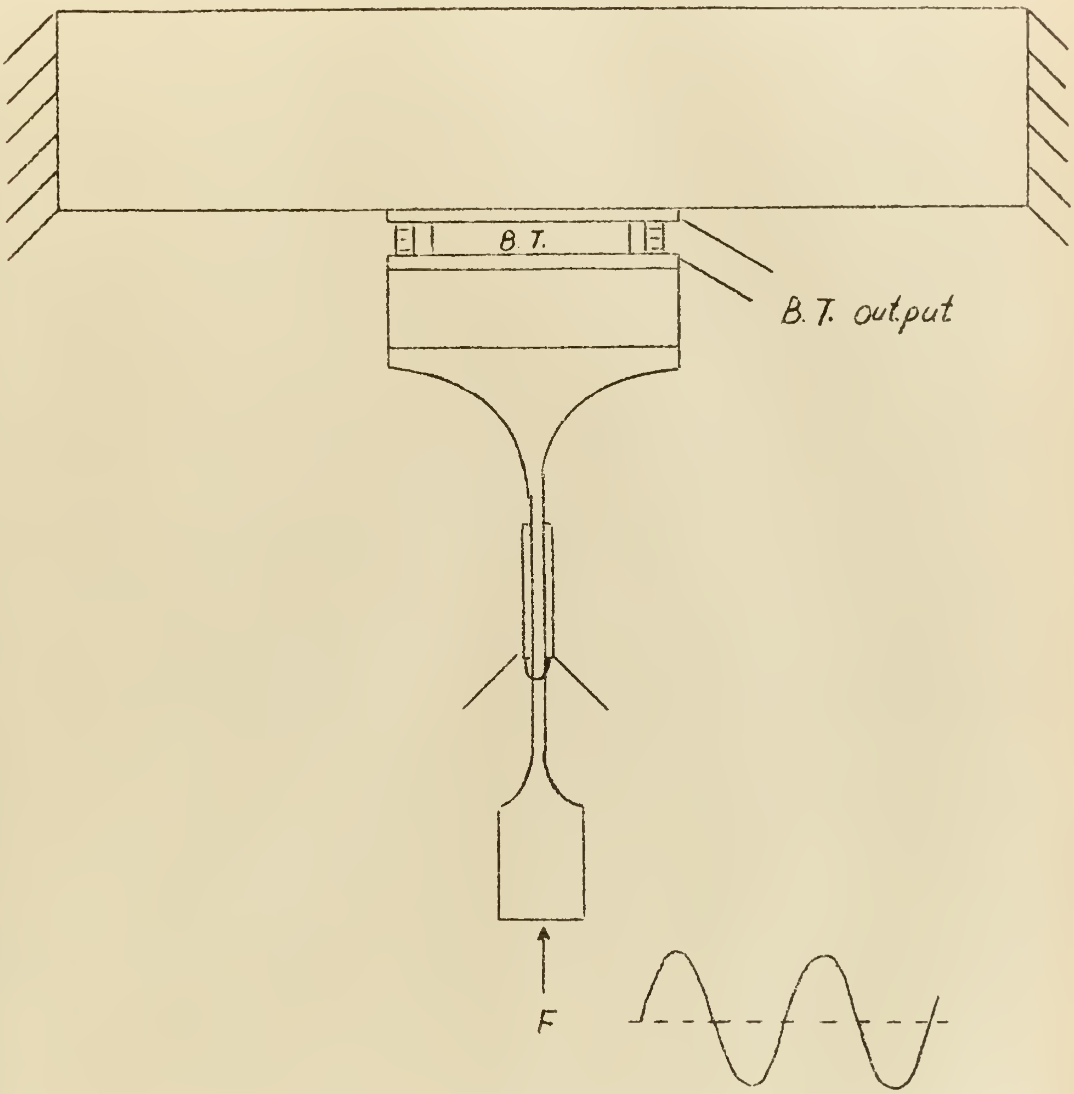


Fig. 10. Suggested method for calibrating B.T.

This method was not tried because of lack of time but would appear to have the advantages of:

a. Adjustable known preloading of B.T.

b. Preloading the springs of the Westinghouse Vibration motor, thereby eliminating wave form distortions near the neutral position resulting from bearing clearances or reversal of bending moment in the cantilever suspension springs.

c. Allow greater forces in the column resulting in a better signal from the SR-4 strain gauge.

d. Minimize actual movement of the B.T., SR-4, and leads in the stray magnetic field surrounding the vibration motor.

A sketch of a proposed (B) end incorporating most of the above proposals is shown in Figure 11. The Endevco model 2501 pressure pickup is manufactured with recess on the sensitive end 13/32 of an inch in diameter and 1/4 inch deep. An optical flat 0.350" diameter by 0.250" high is fitted into the recess and held in place by a stiff silicone grease. The oil bath above the lower flat is filled with the oil under investigation to a sufficient depth to insure that oil at all times fills the space between the upper and lower flats. The loading piston, with its attached optical flat, is inserted in the cylinder which is then capped and the pressure lines connected. If the plane surfaces of the optical flats are not parallel, the leveling screws are adjusted until straight interference bands are observed with the channel spectrometer (not shown).

In use, an actuating pressure is introduced above the loading piston forcing it and its attached optical flat downward through the oil bath to the lower flat resting on the pressure

pickup. Movement of the upper flat with respect to the lower is determined either by a channel spectrum system or an electronic method of counting Haidinger interference fringes.

The actuating pressure might be supplied by almost any means. It is recommended that a small hand pump similar to that on an automobile hydraulic jack be used. Being hand operated, it would permit the application of steady pressures for calibration and/or long loading time tests. It would also permit impulse loading and could easily be modified to allow sinusoidal loading with a motor drive. A bourdon pressure gauge should be inserted in the line for static tests.

The Endevco model 2501 pressure pickup is delivered already calibrated. By mounting it as shown there will be no acceleration or stray electrical effects.

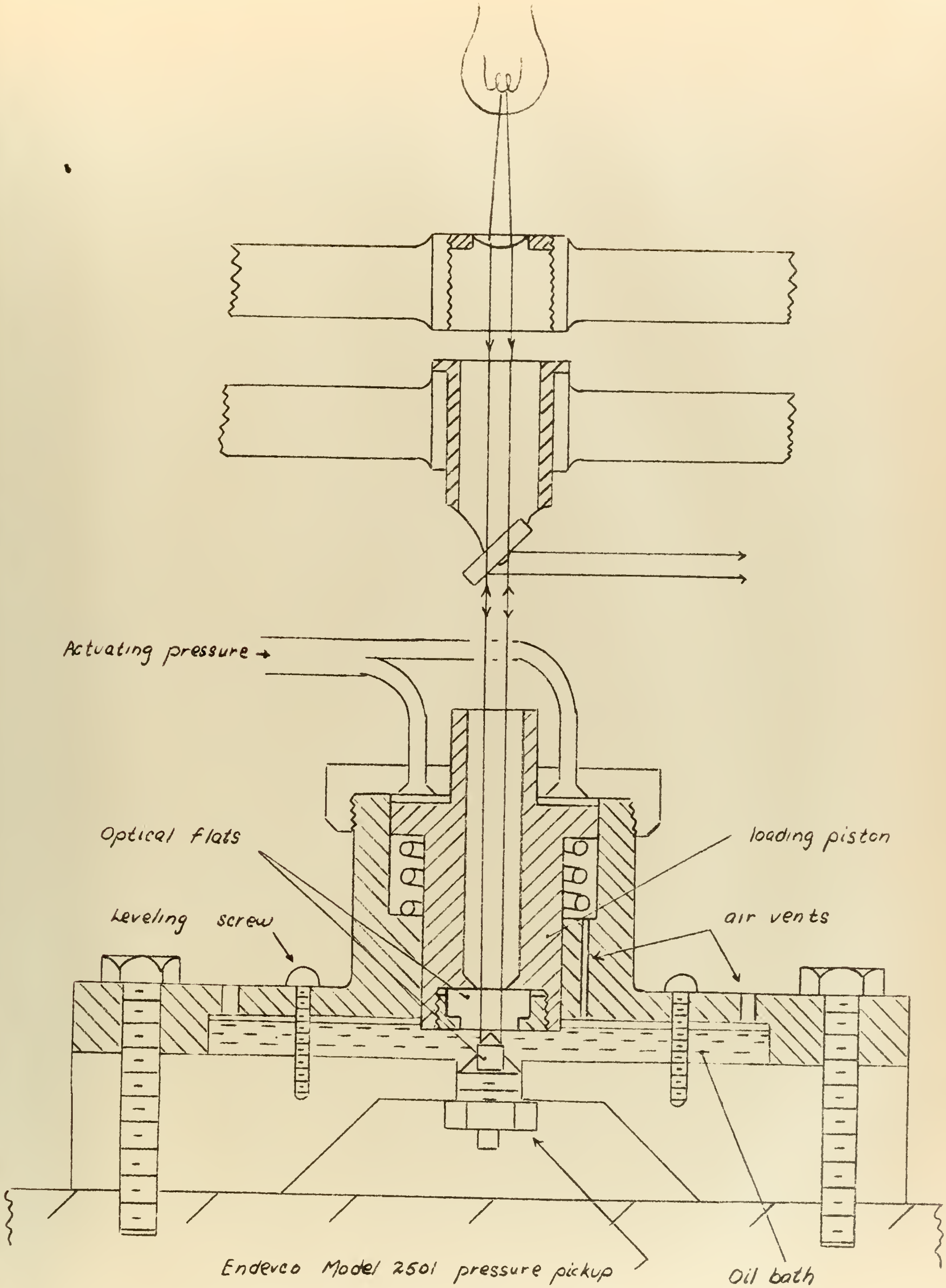


Figure 11. Proposed (B) End

APPENDIX I

The data collected during this investigation is tabulated below, together with explanations for its use.

Table I.

f. Frequency of oscillation (cycles per second). This value was manually set in each case by means of the scale on the controlling oscillator.

Δh. Peak to peak distance of the pressure trace from the B.T. as it appeared on the oscilloscope and referred to the most sensitive scale on the oscilloscope. For example, when the signal was of such strength that it had to be attenuated 100 times as determined by the oscilloscope setting, the actual peak to peak distance of the trace as it appeared on a polaroid photograph was multiplied by 100 and the resulting figure logged under Δ h.

Δs. Peak to peak distance of the strain gauge trace as it appeared on a polaroid photograph of the oscilloscope. The figure listed has been referred to the most sensitive oscilloscope scale as with Δ h. In practice it was always necessary to use the most sensitive scale.

Δ ss. Mean distance between the strain gauge calibrating traces as they appeared on the oscilloscope. In using the Ellis BA-1 indicator, calibration is obtained by an internal chopper system which splits the trace on the C.R.O. into two traces. The distance between the two traces represents

a fixed value Δe. The particular value represented is a function of the strain gauge factor and M, the bridge balancing resistor. In order to obtain the value of Δe represented by Δss, it is necessary to utilize a chart on the inner cover of the BA-1 indicator. In this particular case, the total gauge resistance was 240 ohms, the gauge factor 1.95, and whenever M had the value of 2, the Δe corresponding to the Δss logged in Table I was 61.5 microinches per inch. The value of Δe represented by Δs is then found by simple proportionality.

$$\Delta e = \frac{\Delta s}{\Delta ss} \times 61.5$$

$\Delta h / \Delta e$. C.R.O. scale divisions per microinch of unit strain. The numbers logged in this column are those resulting from the indicated division. It was hoped that all the entries in this column would have the same value. The reasons why they did not are explained in the body of this report. Had the entries in this column been constant, it would have been a simple matter to convert the units such that Δh would have been a direct measure of pressure. For example,

(a) $\Delta F = \Delta e \; AE$

where ΔF = impressed force on the calibrating column.

A = the cross section of the calibrating column.

E = Modulus of elasticity for the supporting column.

The calibrating weight on top of the B.T. pickup was only a fraction of the weight resting on the calibrating column at the gauge section. Let this ratio be K.

Then the pressure on the B.T. pickup would be

(b) $$\Delta P = \frac{K \Delta F}{A'}$$

when A' is the area of the B.T. pickup.

Substituting (a) in (b)

(c) $$\Delta P = \frac{K \Delta e \; AE}{A'}$$

in which Δe is the only variable.

Since the value of $\Delta h / \Delta e$ did not come out a constant, this simple conversion was not carried out. Analysis of the results was based on $\Delta h / \Delta e$ as logged in Table I.

Table II.

f and Δh. These have the same significance as in Table I.

2 r. 2r is the actual distance through which the B.T. pickup was oscillated. In this instance, at any fixed frequency, the pressure on the B.T. was proportional to the amplitude (2r) of vibration.

$$\Delta F = \Delta M \, r \, w^2$$

where ΔF = the change in force on the B.T. pickup

ΔM = the calibrating weight

r = One-half the amplitude of vibration

w = the circular frequency ($2 \pi f$)

Thus $$\Delta F = \frac{0.506 (6.28)^2}{386} r f^2$$

$$\Delta F = 0.0516 \ r \ f^2$$

$$\Delta P = \frac{\Delta F}{A'}$$

where A' is the area of the B.T. pickup as before.

$$\text{Thus } \Delta P = \frac{0.0516 \ r \ f^2}{A'}$$

The pressure is therefore a linear function of r for any given frequency. Δh, however, is not a linear function of Δp (and in turn r) as is shown in Figure 6.

Table III.

This table consists merely of the angle at which known lines of the mercury spectrum were viewed on the spectrometer.

Table IV.

Time. The time in minutes after the assembly of the (B) end. Note that at time = 0, the initial loading of 0.05 psi was applied. This loading resulted from the weight of the upper optical flat itself. At time = 45, an additional loading was applied (total = 0.83 psi) by placing a weight on the (A) end. The first possible reading that was taken after this additional loading was at time = 47, etc.

Δn. The number of dark bands observed in the channel spectrum between θ_1 and θ_2.

θ_1, θ_2. The viewing angle as read from the spectrometer in degrees and minutes.

λ_1, λ_2 . The wave length in angstroms corresponding to

the viewing angle θ_1 or θ_2 as obtained from Figure 12.

t. The oil film thickness in inches/10^4 as determined by the formula

$$t = \frac{1}{2.54 \times 10^8} \times \frac{\Delta n \lambda_1 \lambda_2}{2u(\lambda_1 - \lambda_2)}$$

APPENDIX I

Table I. CALIBRATION OF BARIUM TITANATE

RUN	f	Δh	Δs	Δss	Δe	WT (lbs.)	M	Δh/Δe
1	3000	250	47	72	40.1	0.506	2	6.23
2	5000	340	49	64	47.1	0.506	2	7.21
3	1000	200	47	50	57.9	0.506	2	3.44
4	500	645	42	93	27.8	0.506	2	23.2
5	300	1180	54	86	38.6	0.506	2	30.5
6	200	860	48	105	28.1	0.506	2	30.6
1	3000	-	-	-	-	-	-	-
2	5000	920	53	72	45.3	0.00	2	20.3
3	1000	40	12	46	16.0	0.00	2	2.50
4	500	180	25	100	15.4	0.00	2	11.7
5	300	180	30	88	21.0	0.00	2	8.6
6	200	120	46	103	27.5	0.00	2	4.4
7a	40	510	47	86	33.6	0.506	2	15.2
8	60	520	45	86	32.2	0.506	2	16.1
9	160	240	21	44	11.7	0.506	5	20.5
10	695	650	40	110	36.4	0.506	2	17.7
11	385	500	37	108	34.3	0.506	2	14.6
12	1000	1540	-	-	-	2.71	2	-
13	500	920	50	123	25	2.71	2	36.8

14	300	1360	80	123	40	2.71	2	34.0
15	200	700	45	123	22.5	2.71	2	31.0
16	100	720	50	123	25	2.71	2	28.8
17	50	850	82	123	41	2.71	2	33.1
18	1500	580	50	170	18.1	2.71	5	32.0
19	2000	450	42	170	15.2	2.71	5	29.6
20	3000	360	22	54	25.0	2.71	5	14.4
21	5000	80	13	123	6.5	2.71	2	12.3
22	700	620	24	123	12	2.71	2	51.6
23	800	890	47	123	23.5	2.71	2	37.8
24	900	1360	66	123	33	2.71	2	41.1
25	4000	330	17	123	8.5	2.71	2	38.8
26	400	540	47	123	23.5	2.71	2	23.0
27	600	770	70	123	35	2.71	2	22.0
28	800	740	83	123	41.5	2.71	2	17.9
29	1200	800	58	123	29	2.71	2	27.5

Table II. OPTICAL CALIBRATION

RUN	f	Δh	WT (lbs.)	2 r (in/100)
1	40	38	0.506	0.68
2	40	55	0.506	1.82
3	40	110	0.506	4.31
4	40	155	0.506	5.91
5	40	200	0.506	7.36
6	50	33	0.506	0.591

7	50	55	0.506	1.25
8	50	125	0.506	3.0
9	50	220	0.506	4.51
10	50	345	0.506	5.91
1	40	6.5	0.0	0.68
2	40	10	0.0	1.82
3	40	17.5	0.0	4.31
4	40	24.5	0.0	5.91
5	40	31	0.0	7.36
6	40	5.5	0.0	0.591
7	40	8.5	0.0	1.25
8	40	18.5	0.0	3.0
9	40	31.0	0.0	4.51
10	40	44	0.0	5.91
7a	40	-	-	6.1
8	60	-	-	1.55

Table III. SPECTROMETER CALIBRATION

λ	Color	Angle
4047	Violet	54° - 0'
4358	Blue	53° - 04'
5461	Green	51° - 25'
5770	Yellow_1	51° - 05'
5790	Yellow_2	51° - 02'

Table IV. FILM THICKNESS DATA

TIME	ΔN	θ_1	θ_2	λ_1	λ_2	$\lambda_1 - \lambda_2$	t ($^{in}/_{10^6}$)	psi
0	-	-	-	-	-	-	-	0.05
5	25	51-0	53-08	5875	4375	1500	5.67	0.05
10	20	51-13	53-00	5490	4425	1065	6.05	0.05
15	20	51-13	53-00	5490	4425	1065	6.05	0.05
20	20	51-13	52-55	5490	4460	1030	6.60	0.05
25	20	51-10	52-50	5560	4490	1070	6.20	0.05
30	20	51-15	52-50	5440	4490	950	6.80	0.05
35	20	51-13	52-50	5490	4490	1000	6.52	0.05
40	20	51-13	52-55	5490	4460	1030	6.10	0.05
						Average =	6.25	
45	-	-	-	-	-	-	-	0.83
47	12	51-08	52-30	5630	4625	1005	4.13	0.83
49	12	51-00	52-25	5875	4660	1215	3.59	0.83
53	12	51-03	52-27	5775	4645	1130	3.78	0.83
55	12	51-04	52-28	5745	4640	1105	3.75	0.83
60	12	51-05	52-30	5715	4625	1090	3.87	0.83
65	12	51-06	52-30	5635	4625	1010	4.10	0.83
70	12	51-00	52-25	5875	4660	1215	3.58	0.83
75	12	51-00	52-25	5875	4660	1215	3.58	0.83
						Average =	3.80	
76	-	-	-	-	-	-	-	1.9
80	10	51-00	52-30	5875	4625	1250	2.87	1.9
85	10	51-00	52-25	5875	4660	1215	2.98	1.9

90	10	51-05	52-45	5715	4525	1190	2.88	1.9
95	10	51-00	52-30	5875	4625	1250	2.87	1.9
100	10	51-00	52-30	5875	4625	1250	2.87	1.9
						Average =	2.89	
103	-	-	-	-	-	-	-	3.0
105	10	51-00	52-43	5875	4540	1335	2.64	3.0
110	10	51-00	-	5875	-	-	-	3.0
113	10	51-15	53-15	5440	4325	1115	2.78	3.0
115	10	51-00	52-50	5875	4490	1385	2.33	3.0
117	10	51-00	52-50	5875	4490	1385	2.33	3.0
						Average =	2.52	

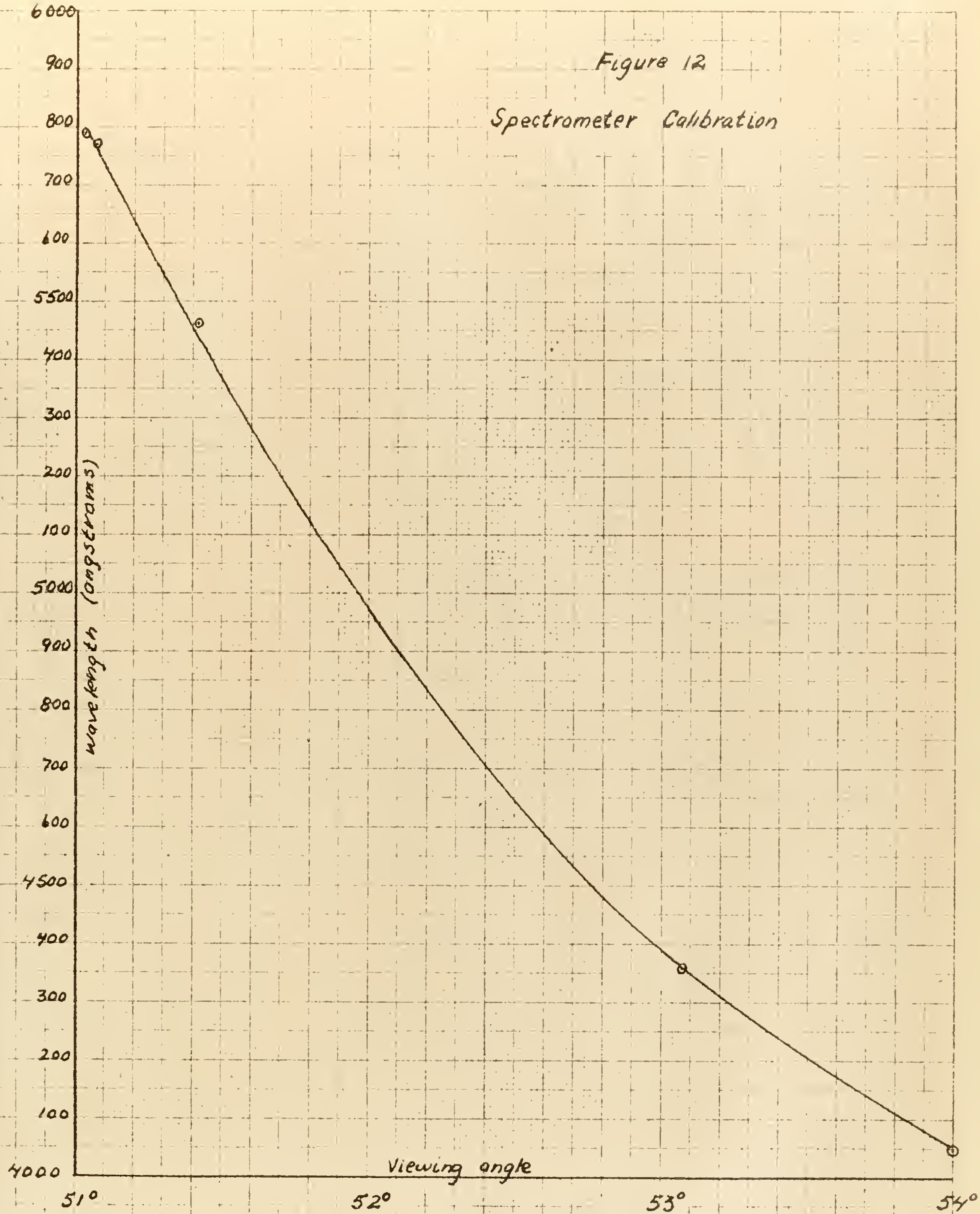


Figure 12
Spectrometer Calibration
6000
900
800
700
600
5500
400
300
200
100
5000
900
800
700
600
4500
400
300
200
100
4000
wavelength (angstroms)
Viewing angle
51°
52°
53°
54°

BIBLIOGRAPHY

1. Brotherton, W. D., Jr. ON THE EXPERIMENTAL DETERMINATION OF THE MINIMUM OIL FILM THICKNESS IN A PLAIN JOURNAL BEARING, Thesis B 8095, USNPGS, 1952.

2. Appert, E. P. MECHANICAL VIBRATION MEASUREMENT, Thesis A 58, USNPGS, 1953.

3. Bridwell, S. L. MECHANICAL VIBRATION MEASUREMENT, Thesis B 807, USNPGS, 1954.

4. A collective work THE MECHANICAL PROPERTIES OF FLUIDS, D. Van Nostrand, 1925.

5. Den Hartog, J. P. MECHANICAL VIBRATIONS, 3rd Edition McGraw-Hill, 1947.

6. Archibald, F. R. LOAD CAPACITY AND TIME RELATIONS FOR SQUEEZE FILMS, Transactions of the ASME, Vol. 78, No. 1, January, 1956.

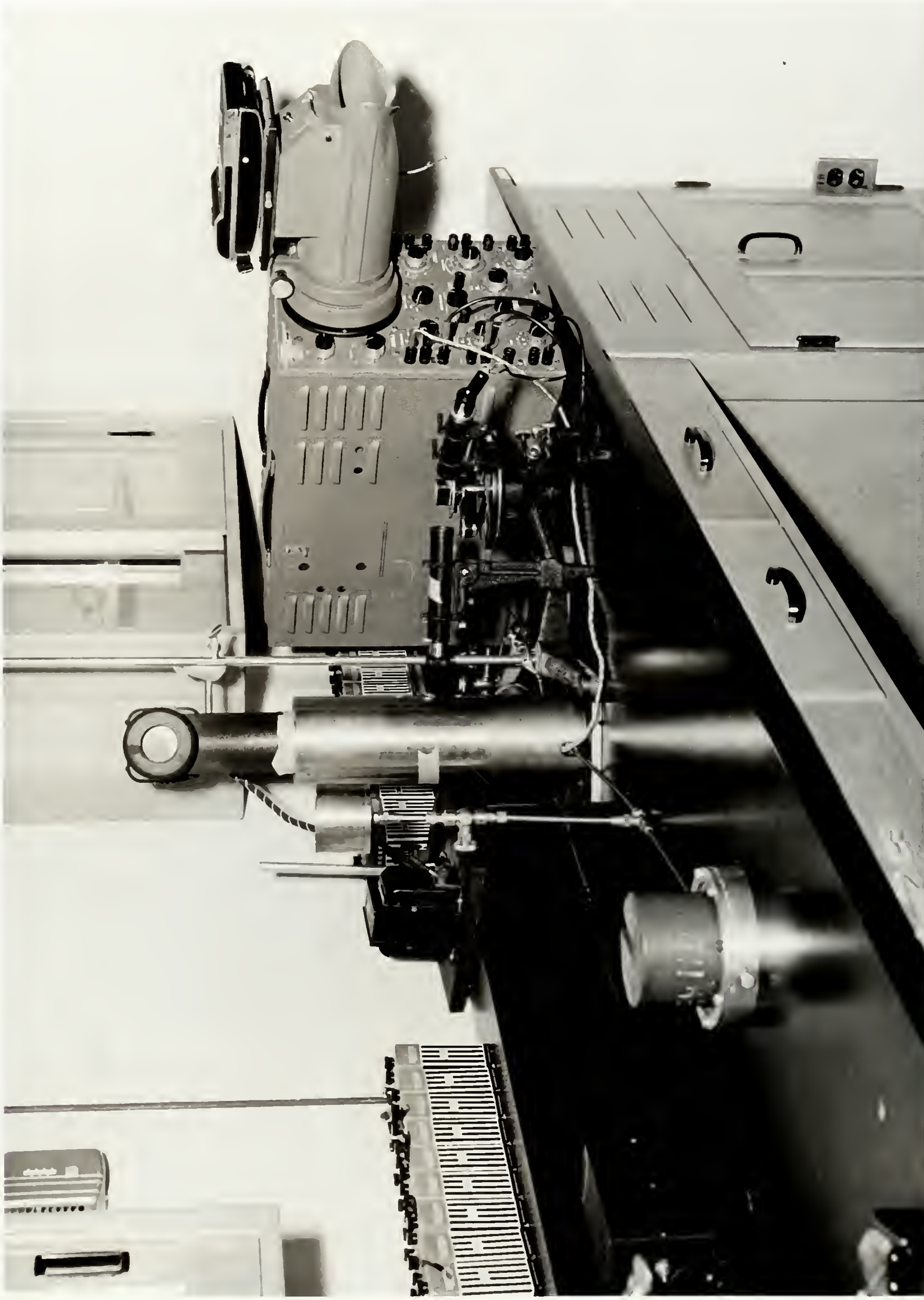
7. Shankland, R. S. ATOMIC AND NUCLEAR PHYSICS, MacMillan, 1955.

8. Kittel, C. INTRODUCTION TO SOLID STATE PHYSICS, John Wiley and Sons, 1953.

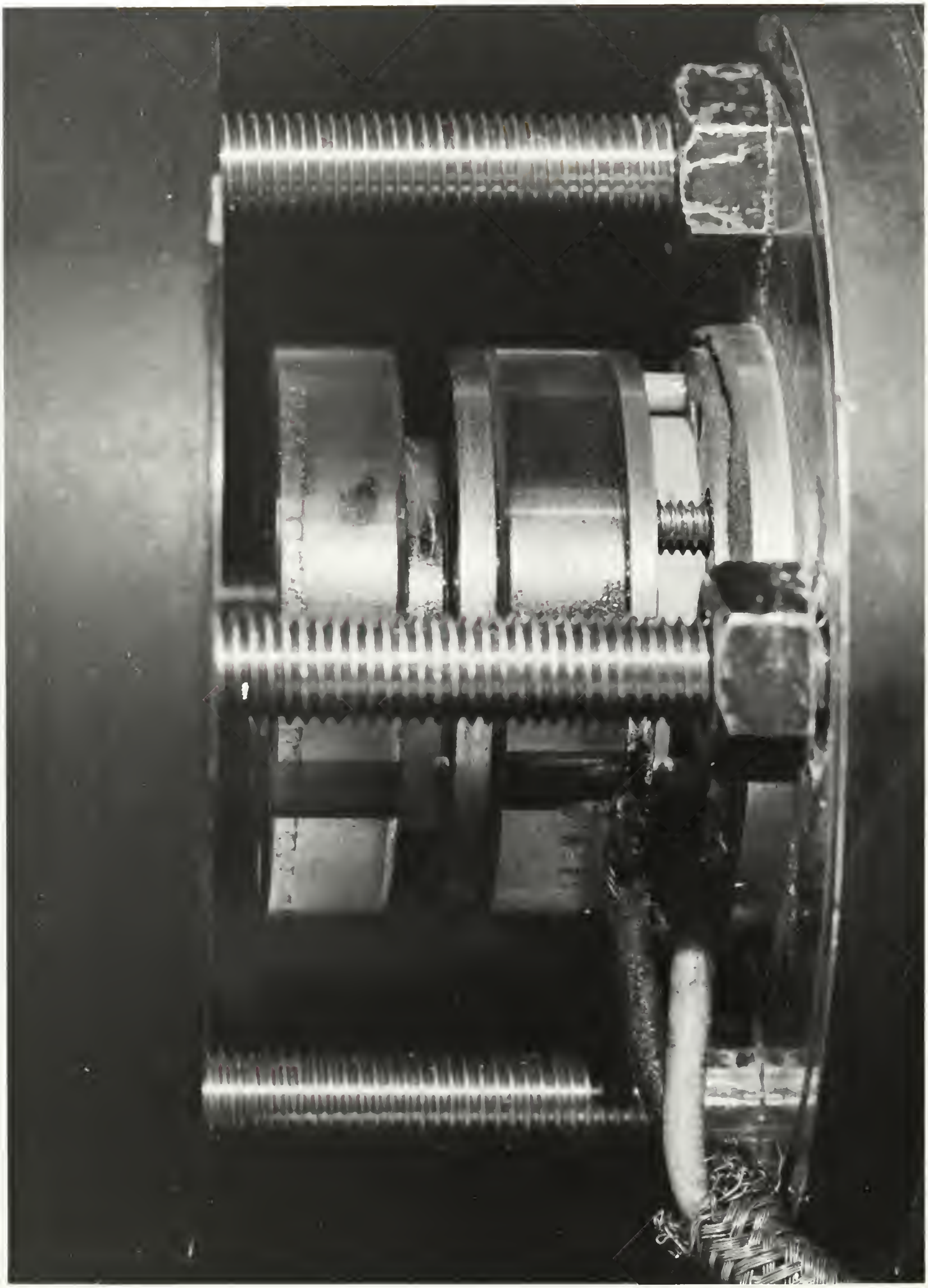
9. Jenkins, F.A. and White, H.E. FUNDAMENTALS OF OPTICS, 2nd Edition, McGraw-Hill, 1950.

10. Hetényi, M. HANDBOOK OF EXPERIMENTAL STRESS ANALYSIS, John Wiley and Sons, 1950.

11. Perry, C. C. and Lissner, H. R. THE STRAIN GAUGE PRIMER, McGraw-Hill, 1955.



The Overall System



(B) End with Optical Flats and Barium Titanate in Place